UCRL-ID-151774

LDRD Final Report Adaptive Methods for Laser Plasma Simulation

Milo R. Dorr (Principal Investigator)
F. Xabier Garaizar
Jeffrey A. F. Hittinger

January 29, 2003

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

This report has been reproduced directly from the best available copy.

Available electronically at http://www.doc.gov/bridge

Available for a processing fee to U.S. Department of Energy
And its contractors in paper from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-mail: reports@adonis.osti.gov

Available for the sale to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-mail: orders@ntis.fedworld.gov
Online ordering: http://www.ntis.gov/ordering.htm

OR

Lawrence Livermore National Laboratory
Technical Information Department's Digital Library
http://www.llnl.gov/tid/Library.html

LDRD Final Report

Adaptive Methods for Laser Plasma Simulation

Tracking Number: 00-ERD-016

Milo R. Dorr (Principal Investigator)
F. Xabier Garaizar
Jeffrey A. F. Hittinger

Center for Applied Scientific Computing
Computation Directorate

January 29, 2003

Executive Summary

The goal of this project was to investigate the utility of parallel adaptive mesh refinement (AMR) in the simulation of laser plasma interaction (LPI). The scope of work included the development of new numerical methods and parallel implementation strategies. The primary deliverables were (*i*) parallel adaptive algorithms to solve a system of equations combining plasma fluid and light propagation models, (*ii*) a research code implementing these algorithms, and (*iii*) an analysis of the performance of parallel AMR on LPI problems.

The project accomplished these objectives. New algorithms were developed for the solution of a system of equations describing LPI. These algorithms were implemented in a new research code named ALPS (Adaptive Laser Plasma Simulator) that was used to test the effectiveness of the AMR algorithms on the Laboratory's large-scale computer platforms. The details of the algorithm and the results of the numerical tests were documented in an article published in the Journal of Computational Physics [2].

A principal conclusion of this investigation is that AMR is most effective for LPI systems that are "hydrodynamically large", *i.e.*, problems requiring the simulation of a large plasma volume relative to the volume occupied by the laser light. Since the plasma-only regions require less resolution than the laser light, AMR enables the use of efficient meshes for such problems. In contrast, AMR is less effective for, say, a single highly filamented beam propagating through a phase plate, since the resulting speckle pattern may be too dense to adequately separate scales with a locally refined mesh. Ultimately, the gain to be expected from the use of AMR is highly problem-dependent.

One class of problems investigated in this project involved a pair of laser beams crossing in a plasma flow. Under certain conditions, energy can be transferred from one beam to the other via a resonant interaction with an ion acoustic wave in the crossing region. AMR provides an effective means of achieving adequate resolution in the crossing region while avoiding the expense of using the same fine grid everywhere, including the region between the beams where no LPI occurs. We applied ALPS to a suite of problems modeling crossed

beam experiments performed on the Omega laser at the University of Rochester. Our simulations contributed to the theoretical interpretation of these experiments, which was recently published in Physical Review Letters [4].

This project has advanced the Laboratory's computational capabilities in the area of AMR algorithms and their application to LPI problems. The knowledge gained and software developed will contribute to the computational tools available for use in the design and interpretation of experiments to be performed at the National Ignition Facility (NIF) in support of Laboratory missions in stockpile stewardship, energy research and high energy density science.

Motivation

The ability to predict and control the interaction of intense laser light with plasmas is critical in the design of laser-driven fusion experiments [5, 7] such as those soon to be conducted at NIF. The plasma generated by the ablation of hohlraum and target materials during the laser pulse can significantly affect the transport of laser energy to the hohlraum wall, the generation of x-rays, and ultimately the uniformity of the radiation pressure on the target. The need to quantitatively predict LPI motivates the development of computational models that include known and hypothesized LPI mechanisms.

As with most computational science problems, the cost of LPI simulations is directly proportional to the number of grid cells needed to resolve important features. Prior to the initiation of our project, all LPI simulators assumed a uniform computational grid. The use of a grid fine enough to sufficiently resolve a wavelength scale feature anywhere in the problem therefore implied the need to use the same resolution everywhere, even in regions outside the beam. Although uniform resolution is adequate for the study of many LPI problems, the question nevertheless arose as to whether AMR could be profitably employed to improve the efficiency of LPI simulations. The current project was undertaken to address this question.

Approach

AMR is not easily retrofitted to an existing code, since it affects every grid-based data structure and has significant implications for the choice of discretization methods. We therefore developed a new code called ALPS (Adaptive Laser Plasma Simulator) for use in testing our adaptive algorithms. ALPS is a hybrid C++/Fortran code built upon the SAMRAI (Structured Adaptive Mesh Refinement Applications Infrastructure) system [3] currently under development in CASC. SAMRAI is a C++ class library designed to reduce the substantial complexity inherent in parallel structured AMR codes by providing many of the data structures and operations that are not specific to the application, allowing code developers to focus on the unique aspects of their particular problem and algorithm. ALPS can be compiled as either a two-dimensional or three-dimensional executable and is parallelized using the Message Passing Interface (MPI) through SAMRAI.

The laser plasma model implemented in ALPS combines a plasma fluid model with a paraxial light propagation model. The plasma model is discretized using a high-resolution upwind method. The paraxial light model is discretized using a Crank-Nicholson finite difference scheme that involves the solution of a complex linear system at each step in the propagation direction. The coupled plasma/light systems are integrated in an operator split fashion. The uniform grid algorithm is extended to locally refined grids using a block-Cartesian strategy. In this approach, the computational domain consists of a hierarchy of refinement levels. Each refinement level is a disjoint union of rectangular grids obtained by refining a subregion of the next coarser level by a fixed ratio in each coordinate direction. The location and number of refinement levels can be dynamically modified during the calculation to follow evolving solution features. The integration of the laser plasma system on the locally refined hierarchy is accomplished by a coordinated integration of the plasma and light systems on individual refinement levels, combined with synchronization steps to enforce the mathematically required compatibility conditions across levels. A complete description of the algorithm is available in [2].

Accomplishments

FY 2000

- *Creation of the ALPS code.* A substantial portion of the project's first year effort focused on the development of a brand new code.

- *Presentation at the 2000 Anomalous Absorption Conference (AAC).* We presented a poster session describing our adaptive algorithm and initial ALPS-computed results. The AAC is the primary international laser plasma physics meeting each year.

- *Presentation at the first SIAM Conference on Computational Science and Engineering.* Contributed talk.

- *Postdoctoral hire.* Dr. Jeffrey A. F. Hittinger was a DOE Computational Science Graduate Fellow at the University of Michigan. For his graduate work under Professor Philip Roe, Dr. Hittinger was named a co-recipient of the first Frederick Anthony Howes Scholar Award, which is administered by the Krell Institute in honor of the late DOE Applied Mathematics Program Manager.

FY 2001

- *Improved light algorithm.* We substantially redesigned our light propagation algorithm to improve the matching of the complex light amplitude at the interface between coarse and fine grids.

- *Improved linear solvers.* The Crank-Nicholson algorithm employed in ALPS to integrate the paraxial light equations requires the solution of a complex linear system at each step in the propagation direction. We replaced an inferior linear solver package with a new complex multigrid solver written by Jim Jones in CASC, which is available through the *Hypre* linear solvers interface.

- *Improved plasma integrator.* To better handle problems with strong ponderomotive drive, we implemented an HLLC (Harten-Lax-Van Leer with restored contact discontinuity) [6] flux algorithm that has better positivity-preserving properties.

- *Journal article completed and published.* The article [2] was written and accepted for publication in the Journal of Computational Physics.

- *Presentation at the 2001 Anomalous Absorption Conference.* Contributed talk.

- *Presentation at the 2001 DOE Computational Science Graduate Fellowship Conference.* Invited talk.

- *Presentation at the 2001 UC Review of Computation.* This work was one of the featured "applications" projects at the UC Review of Computation Directorate research. The Directorate received the top score (Outstanding).

FY 2002

- *Implementation of Richardson extrapolation refinement criteria.* This enabled the AMR grids to be refined based on estimates of the error in the computed solution, rather than (or in addition to) the purely heuristic criteria we had employed previously.

- *Implementation of a Krook model of ion wave damping.* This important physical effect was needed in order to model crossing beam experiments.

- *Implementation of a beam profile import capability.* This allowed, for example, incident beams smoothed by a phase plate to be specified spectrally.

- *Application of ALPS to interpret crossed beam experiments.* In collaboration with X and M Division plasma physicists and NIF experimentalists, we used ALPS to help interpret a set of experiments conducted at the Omega facility at the University of Rochester. Our calculations contributed to a journal article [4] that was published in Physical Review Letters.

- *Presentation at 2002 Anomalous Absorption Conference.* We presented a poster session describing our crossed beam simulations.

- *Project featured in DOE CSGF Annual Report.* We were interviewed by a science writer hired by the Krell Institute to compose an article [1] about our project for the CSGF Annual Report *DEIXIS*. The report included only one article about each DOE Laboratory, and we were selected to represent LLNL.

Collaborations

Throughout this investigation, we have relied heavily upon the assistance and expertise of collaborators in X Division, M Division and the NIF Program: R. L. Berger, A. B. Langdon,

E. A. Williams, C. H. Still, B. I. Cohen, L. Divol, D. E. Hinkel, R. K. Kirkwood and S. H. Glenzer.

References

[1] Victor D. Chase. Housing lasers. In Shelly Olsan, editor, *DEIXIS, The DOE CSGF Annual*, pages 24–27. Krell Institute, www.krellinst.org/CSGF, 2002.

[2] Milo R. Dorr, F. Xabier Garaizar, and Jeffrey A. F. Hittinger. Simulation of laser plasma filamentation using adaptive mesh refinement. *J. Comput. Phys.*, 177(2), 2002. Also available as Lawrence Livermore National Laboratory technical report UCRL-JC-138330.

[3] Richard Hornung and Scott Kohn. The use of object-oriented design patterns in the SAMRAI structured AMR framework. In *Proceedings of the SIAM Workshop on Object-Oriented Methods for Inter-Operable Scientific and Engineering Computing*, October 1998. See `http://www.llnl.gov/CASC/SAMRAI`.

[4] R. K. Kirkwood, P. E. Young, J. D. Moody, A. B. Langdon, B. I. Cohen, E. A. Williams, M. R. Dorr, J. A. F. Hittinger, R. Berger, L. J. Suter, L. Divol, S. H. Glenzer, O. L. Landen, and W. Seka. Observation of saturation of energy transfer between co-propagating beams in a flowing plasma. *Phys. Rev. Lett.*, 89(21):215003(4), 2002.

[5] R. W. Lee, R. Petrasso, and R. W. Falcone. Science on high-energy lasers: From today to NIF. Technical Report UCRL-ID-11970, Lawrence Livermore National Laboratory, June 1995.

[6] E. F. Toro, M. Spruce, and W. Speares. Restoration of the contact surface in the HLL-Riemann solver. *Shock Waves*, 4(1):25–34, 1994.

[7] C. Yamanaka. *Introduction to Laser Fusion*. Harwood Academic Publishers, Chur, Switzerland, 1991.